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Influence of the built-up edge on the stress state in the chip formation zone during orthogonal cutting of AISI1045

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Abstract

In-situ strain measurements with high energy synchrotron radiation during orthogonal cutting of AISI1045 were carried out. Thereby it was possible to determine the stress state in the chip formation zone during the cutting process. As such, observations regarding the formation of built-up edges during the cutting process have been made. The formation of a built-up edge on the cutting tool is a common phenomenon during cutting of mild steel and other ductile materials, in particular at low cutting speeds. This may result in increased tool wear and a decrease in the resulting surface quality. By analyzing the chip roots of the in-situ experiments, it was possible to determine the geometry of the built-up edges on tools with a rake angle of $\gamma = 0°$ and cutting edge radii of $r_\beta = 30$ µm and $r_\beta = 60$ µm. Using the obtained data a simulation model which represents the built-up edge could be established with two versions of the built-up edge: a solid one as part of the rigid tool and an elastic one in front of the tool. Using FEM cutting simulations with and without built-up edges, it was possible to show the influence of a built-up edge on the chip formation and the stress state in the chip formation zone. With this data, a comparison of the results of the cutting simulations with those of the in-situ experiments was conducted.

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Keywords: Chip; Cutting edge; Simulation; Stress

1. Introduction

The formation of a built-up edge (BUE) is a common phenomenon in particular during the machining of ductile materials [1, 2]. The grade of the BUE formation depends on the workpiece material, the tool geometry and the process parameters. Especially during the machining of carbon steels with cutting speeds of $v_c = 60$ m/min and less the formation of a BUE often occurs [3] due to the low temperatures in the chip formation zone [4]. Thereby, the hardened workpiece material sticks to the cutting edge and the rake face and forms a new tool geometry with a smaller wedge angle and a bigger rake angle [5]. Thus the chip formation and the stress state in the chip formation zone are influenced as well as the tool wear, the surface quality, the cutting forces and temperatures [1, 6]. The separation of the BUE from the cutting tool leads to damage of the tool and thus to an increase of the tool wear [7]. Furthermore the undefined geometry of the tool with a BUE and the aperiodic separation of the BUE can lead to a poor surface quality of the workpiece and vibrations during the cutting process [8].

Several investigations on the BUE have been undertaken in the past. Opitz and Gappisch examined the coherence of the BUE formation with the used workpiece material, the process

Nomenclature

BUE	built-up edge
h	undeformed chip thickness
l_e	edge length of an element in the FE-Simulation
m	shear friction coefficient
r_β	cutting edge radius
t	exposure time
v_c	cutting speed
φ	plastic strain
γ	rake angle
μ	Coulomb friction coefficient

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parameters and the tool geometry [5]. It was found that the ductility of the workpiece material and the cutting speed have a significant influence. Fang and Dewhurst analysed the BUE formation and proposed a slip line model [1]. They investigated the influence of the rake angle on the size of the BUE. Childs developed a material model for the simulation of the BUE formation [4, 9, 10] and applied it at the micro-machining scale [9]. It was determined that the damage law, which was implemented in the simulation is very important for the initialisation of the BUE formation [4]. Kümmel et al. investigated the microstructure of the BUE and concluded a possible protecting effect for the tool [11]. In a further work they examined the microstructure of the tool surface in order to stabilise the BUE as a protection layer on the tool surface [12]. Until now it was not possible to analyze the influence of a BUE on the stress state in the chip formation zone with the use of experimental determined data. This paper aims to present the results of investigations, which were carried out in this way.

2. In-situ strain measurements

By the use of high energy synchrotron radiation it was possible to determine the strain state and thus the stress state in the chip formation zone during orthogonal cutting [13]. A special experimental setup for measurements at the PETRA III storage ring at DESY, Hamburg was developed for this purpose [14]. With this setup it was possible to position a X-ray beam on a sample of AISI1045 during an orthogonal cut. The beam has a size of 20 µm x 20 µm. Different measuring positions in the chip formation zone have been defined in order to gain detailed information regarding the stress state in the chip formation zone. The setup of the cutting experiment was therefore placed between the X-ray beam source and the 2D detector (type MAR345, Marresearch, Norderstedt, Germany) which captured the diffraction patterns. The diffraction experiments were carried out according to the Debye–Scherrer method [15].

The cutting speed is limited to $v_c = 3$ mm/min. This is due to the long exposure time of $t = 30$ s and the need for a very stiff cutting setup to avoid a displacement of the measuring position during the in-situ experiment. Unfortunately this very low cutting speed favours the formation of a BUE. The used cutting inserts are made of cemented carbide (grade IC20, ISCAR Germany GmbH, Ettlingen) and have the ISO-geometry SPUN 120304 with a rake angle of $\gamma = 0°$ and a cutting edge radius of $r_\beta = 6$ µm. In addition cutting edge radii of $r_\beta = 30$ µm and $r_\beta = 60$ µm were prepared by brushing. A more detailed description of the experimental setup is described by Uhlmann et al. [14].

Through the analysis of the data obtained by the in-situ strain measurements, it was possible to develop and validate a material model for the cutting simulation of AISI1045. The simulations with this model showed a good qualitative and partially quantitative accordance in comparison to the experimentally determined data. This confirms the quality of the material model. An investigation of the experimentally determined stress state in the chip formation zone resulted in new findings with regard to the shear angle model by Opitz and Hucks [14, 16].

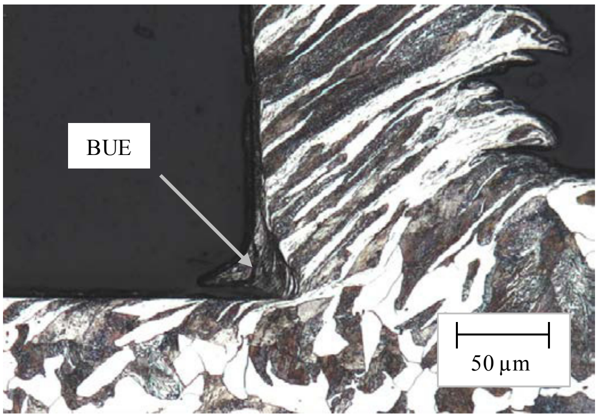

Fig. 1. BUE at the chip root of a tool with $\gamma = 0°$ and $r_\beta = 30$ µm.

The analysis of the chip roots showed evidence that BUEs appeared during the in-situ strain measurements for certain cutting parameters. This is a common phenomenon for the low cutting speed of $v_c = 3$ mm/min. Tools with a cutting edge radius of $r_\beta = 30$ µm und $r_\beta = 60$ µm showed remains of a BUE in the analysis of the chip roots. Figure 1 shows a chip root after an in-situ experiment. The used tool had a rake angle of $\gamma = 0°$ and a cutting edge radius of $r_\beta = 30$ µm. The undeformed chip thickness is $h = 0.06$ mm. A BUE at the cutting edge can clearly be seen.

The formation of a BUE inevitably has an influence on the stress state in the chip formation zone. Thus a detailed examination of the stress state under the influence of a BUE is useful in order to investigate the results in comparison to the experimental results for cutting parameters where the formation of a BUE is indicated.

3. Simulation model

In order to examine the influence of the BUE on the stress state in the chip formation zone, simulations were carried out with the software DEFORM 2D v11.0.1, Scientific Forming Technologies Corporation, Columbus, USA. The necessary material model is based on yield curves, which were determined by compression tests. For this purpose a Rastegaev geometry was used which maintains its cylindricity during the compression test up to plastic strains of $\varphi = 0.6$ [17]. With the findings of the in-situ strain measurements the material model was adapted and validated [14].

A hybrid friction model was used in order to reproduce the friction condition between cemented carbide and AISI1045. The hybrid friction model is a combination of a Coulomb friction model and a shear friction model. The Coulomb friction coefficient was carried out by friction tests to be $\mu = 0.5$ and the shear friction coefficient was set to $m = 0.58$ [14]. Together with the material model this combination showed the best agreement between the stresses determined by the experiment and those of the simulation [14].

Simulations with and without the BUE were carried out in order to investigate the influence of the BUE on the stress state in the chip formation zone. The process was depicted as a rigid-plastic FEM model. Since tools with the rake angle

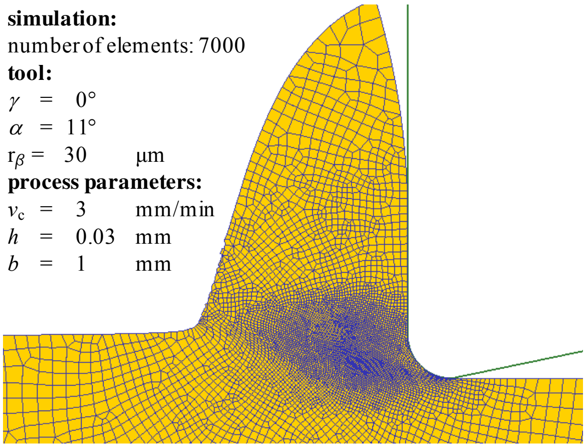

Fig. 2. FEM-model of the cutting process in DEFORM 2D.

$\gamma = 0°$ and cutting edge radii of $r_\beta = 30$°µm and $r_\beta = 60$°µm showed the greatest disposition for forming a BUE, simulations with these parameters and the undeformed chip thickness of h = 30 µm were carried out. The geometry of the BUE was determined by the analysis of chip roots of the in-situ experiments.

Figure 2 shows the simulation model. It consists of approximately 7,000 elements, due to remeshing procedures the exact number of elements varies during the simulation. However, different mesh windows were used to define regions with a finer mesh. The smallest elements with an edge length of approx. $l_e = 1.5$ µm are located around the cutting edge and the BUE.

The BUE was realised in the simulations in two different ways. The first one was a reproduction of the BUE as a part of the rigid tool. The second variant was an elastic BUE, which was placed in front of the cutting edge (Figure 3). The elastic BUE has a Young's modulus of E = 207,000 MPa and a Poisson ratio of $\nu = 0.3$. The friction coefficient between the BUE and the workpiece was set to $\mu = 0.15$ which is a typical value for the friction between steel and steel [18]. The geometry of the BUE was extracted with the software Matlab R2011a, MathWorks Inc., Natic, USA from optical microscopy images that were taken from the chip roots as shown in Figure 3. Normally the formation of a BUE is an unsteady process. Nevertheless for first investigations this behaviour is not considered. Table 1 gives an overview of the simulations that were carried out.

4. Results

4.1. Forces and shear angles

The cutting and passive forces, F_c and F_p, that were measured during the in-situ experiments and from the simulations are given in Table 2 for a cutting edge radius of $r_\beta = 30$ µm. The integration of a BUE in the simulations reduces the forces. The BUE changes the geometry of the tool. The properties are comparable with those of a tool with a higher rake angle and a sharper cutting edge. The grade of reduction of the forces is higher in the simulation with the elastic BUE. The elastic BUE reduces the forces to approximately 50 % of the values of the simulation without a BUE, the solid method to approximately 60 %.

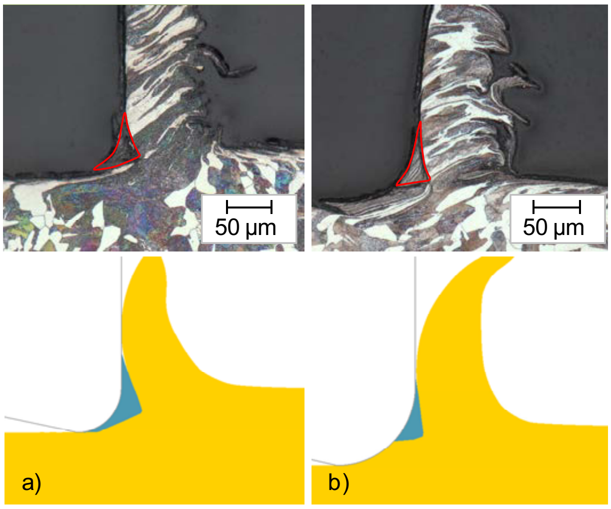

Fig. 3. BUEs at the chip roots and the corresponding FEM-simulations with different cutting edge radii: (a) $r_\beta = 30$ µm; (b) $r_\beta = 60$ µm.

Table 1. Parameters of the simulations with and without a BUE

BUE	Cutting speed v_c [mm/min]	Undeformed chip thickness h [µm]	Rake angle γ	Cutting edge radius r_β [µm]
Solid	3	30	0°	30, 60
Elastic	3	30	0°	30, 60
None	3	30	0°	30, 60

Compared to the forces that were measured during the in-situ experiments the simulation without the BUE gives the best results. However earlier investigations showed that the implemented simulation model with the hybrid friction model underestimates the cutting forces, especially the passive force F_p [14]. Nevertheless this model showed the best accordance when comparing the stresses of the experiment and the simulation. For this reason the simulation model with the hybrid friction model was used for the investigations.

Table 3 shows the forces from the experiments and the simulation for the cutting edge radius of $r_\beta = 60$ µm. As before, the BUE reduces the cutting force F_c. However, the passive force F_p increases for the simulation with a solid BUE. For this simulation the cutting force F_c and the passive force F_p are equal. The elastic BUE reduces the cutting and the passive force. In contrast to the simulation without the BUE the passive force Fp is now higher than the cutting force

Table 2. Cutting and passive forces of the simulations and experiments with the cutting edge radius of $r_\beta = 30$ µm

$r_\beta = 30$ µm	Cutting Force F_c [N]	Passive Force F_p [N]
Simulation with solid BUE	63	50
Simulation with elastic BUE	50	45
Simulation without BUE	100	83
Experiments	112	79

Table 3. Cutting and passive forces of the simulations and experiments with the cutting edge radius of $r_\beta = 60$ µm

$r_\beta = 60$ µm	Cutting Force F_c [N]	Passive Force F_p [N]
Simulation with solid BUE	95	95
Simulation with elastic BUE	41	55
Simulation without BUE	114	80
Experiments	144	115

BUE and the cutting edge in the applied model. The BUE geometry has a significant influence on the cutting process. Further investigations with a variation of the geometry should clarify this.

A comparison of the forces from the simulations and the experiments shows results that are similar to those with the cutting edge radius $r_\beta = 30$ µm. The simulation without the BUE reveals the best results. However, compared to the experiments the forces of the simulation without the BUE are too low.

A comparison of the shear angles is a second possibility to evaluate the quality of the simulations (table 4). The influence of the BUE on the shear angle is clear. Both the solid and the elastic BUE increase the shear angles for the cutting edge radii $r_\beta = 30$ µm and $r_\beta = 60$ µm. Thereby the shear angle for $r_\beta = 30$ µm is slightly higher. Furthermore the elastic BUE increases the shear angle more than the solid BUE. The shear angles from the in-situ experiments were measured with the use of the optical microscopy images from the chip roots. For each cutting edge radius three different samples were analysed. Thus the shear angles vary between $\Phi = 16°$ and $\Phi = 21°$ for $r_\beta = 30$ µm and between $\Phi = 13°$ and $\Phi = 18°$ for $r_\beta = 60$ µm. The simulation without the BUE gives shear angles at the bottom of this range and for the elastic BUE the shear angles are at the top of this range. The solid BUE overestimates the shear angles.

In conclusion after the analysis of the forces and the shear angles, the simulation without the BUE gives the best results compared with the in-situ experiments. The BUE reduces the forces within the simulations and increases the shear angles. At this time it is not possible to determine if the solid BUE or the elastic BUE gives better results.

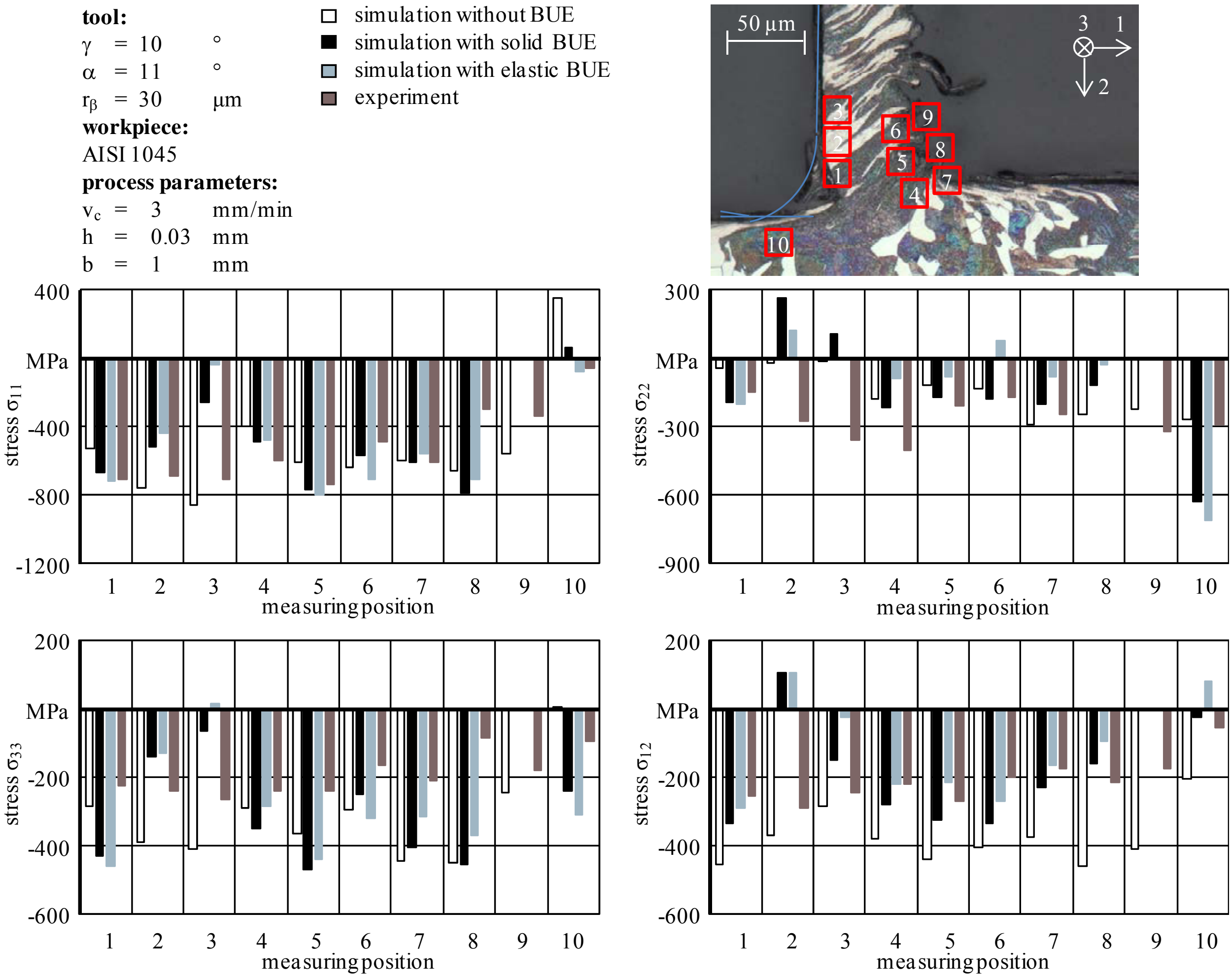

Fig. 4. Results from the simulation without a BUE, with a solid and elastic BUE, and from the experiments with a cutting edge radius of the tool of $r_\beta = 30$ µm.

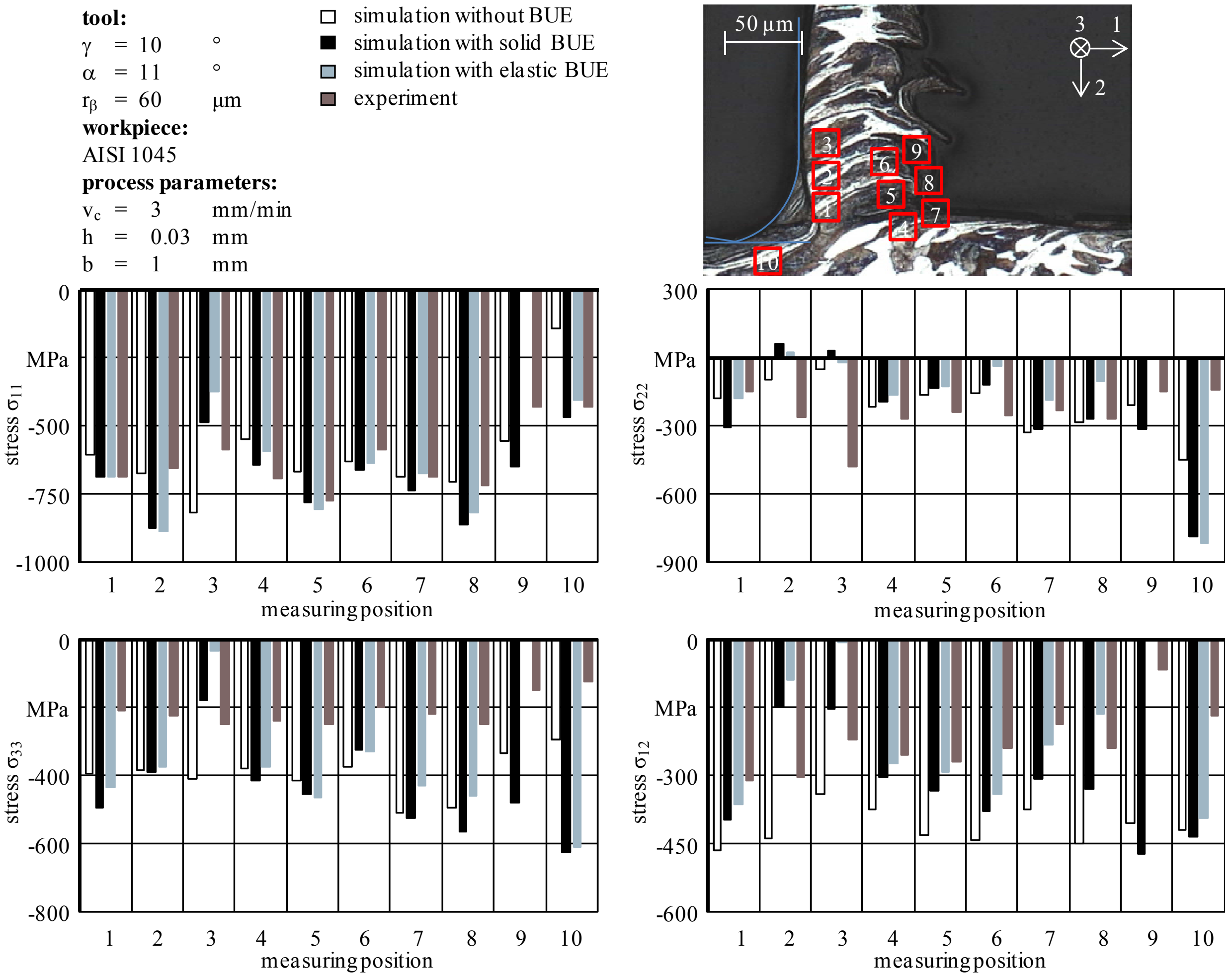

Fig. 5. Results from the simulation without a BUE, with a solid and elastic BUE, and from the experiments with a cutting edge radius of the tool of $r_\beta = 60$ µm

Table 4. Shear angles Φ

	$r_\beta = 30$ µm	$r_\beta = 60$ µm
Simulation with solid BUE	21°	19°
Simulation with elastic BUE	24°	21°
Simulation without BUE	15°	14°
Experiments	16° - 21°	13° -18°

4.2. Stress state in the chip formation zone

With the in-situ experiments it is possible to compare the stresses in the chip formation zone that were determined with cutting simulations with experimental data for the first time. Figure 4 shows the results of the simulations without the BUE, with the solid and the elastic BUE compared with the experimental derived data. The normal stresses σ_{11}, σ_{22}, σ_{33} and the shear stresses σ_{12} are given. The simulated stresses were averaged over several points and simulation steps. Thus, the spatially and temporally integrative character of the in-situ strain measurements is taken into account. Earlier investigations showed that the simulation model achieves the best qualitative and quantitative results for the normal stresses σ_{11} and the shear stresses σ_{12} [14]. The normal stress σ_{22} cannot be reproduced by the simulation model in a good quality.

Similar results can be seen in figure 4 for the cutting edge radius $r_\beta = 30$ µm. All simulations achieve a good accordance for the stresses σ_{11} and σ_{12}. For the simulations with a BUE measuring position 9 (MP9) is outside of the workpiece material. Thus there are no results for this MP and for these simulations. The most interesting MPs are number 1, 2, 3 and 10. They are very close to the cutting edge and the BUE has the biggest influence on these MPs. For σ_{11} the simulations with the BUE achieve a very good accordance with the experimentally determined stress for MP1. For MP2 and 3 σ_{11} is understimated by the simulations with the BUE. At MP10 a negative stress σ_{11} was measured during the in-situ experiments. The simulation without a BUE gives a positive stress for this MP. The simulation with a solid BUE reduces the stress and with the elastic BUE a negative stress can be achieved. At the other MPs the simulation without the BUE achieves a good correlation for the stress σ_{11}. The simulations with a BUE do not increase the correlation of the results. The simulation without the BUE overestimates the stresses σ_{12} for the majority of the MPs. With the elastic and the solid BUE the results can be improved for some of the MPs. As expected from earlier investigations [14] the simulations are not able to achieve a good correlation for the stresses σ_{22}. The integration of the BUE does not change this behaviour.

Figure 5 shows the results for the cutting edge radius $r_\beta = 60$ µm. For the elastic BUE MP9 is again positioned outside of the workpiece material. A good correlation for the stresses σ_{11} can be achieved by the simulation without the BUE, except for the MPs 3 and 10. Especially for MP10 the simulations with the BUE are very close to σ_{11} determined by the experiment. The results for the shear stress σ_{12} with $r_\beta = 60$ µm are very similar to those that were achieved with $r_\beta = 30$ µm. For all MPs the simulation without a BUE overestimates the stresses. The BUE reduces the stresses and at five out of ten MPs the elastic BUE achieves a good correlation with the experiment. Due to the BUE geometry, which is comparable to a tool with a positive rake angle, the shear stresses in the 12-plane are lower.

5. Conclusion and outlook

The in-situ strain measurements that were carried out with high energy synchrotron radiation gave several indications for the formation of BUEs during the experiments especially with tools with a rake angle of $\gamma = 0°$ and cutting edge radii of $r_\beta = 30$ µm and $r_\beta = 60$ µm. Thus simulations with BUEs have been carried out. An elastic and a solid BUE as part of the tool were implemented after determining the BUE geometry by analysing the chip roots of the in-situ experiments. The investigations showed that the simulations with the BUE reduces the forces and increases the shear angles. The analysis of the stress state in the chip formation zone gave no clear result. For the shear stresses σ_{12} a better correlation with the experiments can be achieved with the integration of the BUE. The elastic BUE gave the best results for σ_{12}. The simulation without the BUE gave good results for the normal stresses σ_{11}. The simulations with the BUE did not improve the correlation. The results for the stresses σ_{22} and σ_{33} vary. The grade of the correlation depends on the measuring position and the chosen simulation. Further investigations shall be undertaken to finally clarify the influence of the BUE on the stress state. Since the geometry of the BUE has a big influence on the cutting process, a variation of the BUE geometry should taken into consideration. As a final step the simulation of the BUE formation combined with a damage model would be preferable.

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